Impact of Military JP-8 Fuel on Heavy Duty Diesel Engine Performance and Emissions

Gerald Fernandes[1], **Jerry Fuschetto**[1], **Zoran Filipi**[1] **and Dennis Assanis**[1]

Heather McKee[2]

[1]University of Michigan, Automotive Research Center, Ann Arbor, USA

[2]US Army RDECOM National Automotive Center, Warren, USA

ABSTRACT: The US army single fuel forward policy mandates that deployed vehicles must refuel with aviation fuel JP-8, and when that is not available, are permitted to use diesel. The US army is expected to use JP-8 till year 2025. There is a known torque and fuel economy penalty associated with the operation of a diesel engine with JP-8 fuel due to its lower density and viscosity, but few experimental studies suggest that kerosene-based fuels have the potential for lowering exhaust emissions (especially particulate matter) compared to typical distillate fuels such as diesel #2. However, studies so far were typically focused on quantifying effects of simply replacing the regular diesel fuel with JP-8, rather than fully investigating the reasons behind the observed differences. This research evaluates the effect of using JP-8 fuel in a heavy duty diesel engine on fuel injection, combustion, performance and emissions, and subsequently utilizes the obtained insight to propose engine calibration capable of minimizing the possible penalties. Test experiments were carried out on a Detroit Diesel Corporation (DDC) S60 engine outfitted with EGR. The results indicate that torque and fuel economy of diesel fuel can be matched without smoke or NOx penalty by increasing the duration of injection to compensate for lower density. The lower cetane number of JP-8 led to higher ignition delay and increased premixed combustion, but adjusting of injection timing to keep the ignition timing unchanged had a minor effect. Under almost all conditions, JP-8 led to lower NOx and PM emissions and shifted the NOx-PM tradeoff favorably.

Keywords: Diesel Engine, Aviation Fuel, JP-8, Emissions, Calibration

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **07 DEC 2005**	2. REPORT TYPE **Technical Report**	3. DATES COVERED **07-12-2005 to 07-12-2005**

4. TITLE AND SUBTITLE **IMPACT OF MILITARY JP-8 FUEL ON HEAVY DUTY DIESEL ENGINE PERFORMANCE AND EMISSIONS**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Heather McKee; Gerald Fernandes; Jerry Fuschetto; Zoran Filipi; Dennis Assanis**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC ,6501 E.11 Mile Rd,Warren,MI,48397-5000**	8. PERFORMING ORGANIZATION REPORT NUMBER **#15355**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC, 6501 E.11 Mile Rd, Warren, MI, 48397-5000**	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S) **#15355**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Co-Authored with University of Michigan, Automotive Research Center (ARC), Ann Arbor, MI

14. ABSTRACT
The US army single fuel forward policy mandates that deployed vehicles must refuel with aviation fuel JP-8, and when that is not available, are permitted to use diesel. The US army is expected to use JP-8 till year 2025. There is a known torque and fuel economy penalty associated with the operation of a diesel engine with JP-8 fuel due to its lower density and viscosity, but few experimental studies suggest that kerosene-based fuels have the potential for lowering exhaust emissions (especially particulate matter) compared to typical distillate fuels such as diesel #2. However, studies so far were typically focused on quantifying effects of simply replacing the regular diesel fuel with JP-8, rather than fully investigating the reasons behind the observed differences. This research evaluates the effect of using JP-8 fuel in a heavy duty diesel engine on fuel injection, combustion, performance and emissions, and subsequently utilizes the obtained insight to propose engine calibration capable of minimizing the possible penalties. Test experiments were carried out on a Detroit Diesel Corporation (DDC) S60 engine outfitted with EGR. The results indicate that torque and fuel economy of diesel fuel can be matched without smoke or NOx penalty by increasing the duration of injection to compensate for lower density. The lower cetane number of JP-8 led to higher ignition delay and increased premixed combustion, but adjusting of injection timing to keep the ignition timing unchanged had a minor effect. Under almost all conditions, JP-8 led to lower NOx and PM emissions and shifted the NOx-PM tradeoff favorably.

15. SUBJECT TERMS
diesel enigine, aviation, fuel, jp-8, emissions, calibration

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**20**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

NOTATION

BOI	Beginning of Injector Energizing
CN	Cetane Number
D-2	Diesel Fuel Type 2
EGR	Exhaust Gas Recirculation
EUI	Electronic Unit Injector
JP-8	Jet Propellant 8, kerosene based
LHV	Lower Heating Value, net
PM	Particulate Matter
PW	Injection Pulse Width
SOC	Start of Combustion
SOI	Start of Injection (actual)
VGT	Variable Geometry Turbocharger

INTRODUCTION

Diesel engine is a prime-mover of choice for military off-highway and combat vehicles. Turbocharged diesel offer high power density, robustness and favorable reliability. While the commercial world relies on fuels tailored specifically for use in diesel engines, simplification of the army logistics dictated reducing the total number of fuels down to a minimum. In particular, using a single fuel for both aircraft jet-engines and vehicular diesels offers a chance for huge benefits. According to Army logistics, about 38.6 percent of troop supply is bulk fuel. A desperate need to have some standardization of fuel to save fuel costs and optimize logistics was identified [1]. The U.S. and NATO jointly switched to kerosene-based Jet A-1 fuel to power the jet engines for aircrafts, since they are less likely to explode (less volatile) as compared to previously used JP-4 fuel (gasoline-kerosene mix) and hence considered safer for handling. Additionally, it was identified that Jet A-1 had properties similar to winter Diesel Fuel (DF-1). Hence the U.S. Army adopted the strategy of a "single fuel forward", aviation kerosene fuel MIL-T-83133C grade JP-8 with a maximum allowable sulfur content of 0.3 percent (3000 ppm) by weight for the battlefield. The only difference between Jet A-1 and JP-8 is the addition of three fuel additives [2].

Modern diesels are designed for both military and commercial applications, but their base calibrations are typically developed with diesel fuel in mind. Hence, operating standard engines with JP-8 leads to non-optimal performance. Capabilities of state-of-the-art electronic control units make dual-use calibrations viable; however, better understanding of the fundamental effects of JP-8 on engine operation is required before they can be developed. Approach to correlating fuel properties with diesel engine performance and emissions can be of broader interest, given the recent focus on alternative commercial diesel fuels, such as the synthetic diesel or bio-diesel.

The effects of the use of JP-8 on diesel engine performance and emissions in a diesel engine are not fully understood. Most of the tests with JP-8 have been done on standard test cycles to generate cumulative numbers, and they provide a valuable indication of the overall impact of replacing diesel fuel with JP-8 [2, 3, 4]. Recently, a study was conducted by Frame et al. [5] to investigate the use of a synthetic jet fuel in a medium-duty diesel engine, with a particular focus on studying the wear in the pump due to lower lubricity of the fuel, rather than calibration. In response to a renewed interest by NATO to monitor and improve the quality of JP-8, a study was conducted by Korres et al. [6] to determine the impact of replacing diesel fuel with JP-8 in a single-cylinder diesel engine, but without an in-depth investigation of combustion effects behind observed global trends or recommendations for mitigating them to improve engine performance. In summary, while valuable data is available regarding direct replacement of standard diesel fuel with JP-8, there is a clear need to better understand and quantify the fundamental reasons for observed changes, and to subsequently propose strategies for eliminating potential drawbacks. There could be benefits too, e.g. there are indications that kerosene-based fuels such as JP-8 can produce lower soot emissions than a diesel. Visual signature is directly related to soot, and it remains an important issue in training and combat missions. The EPA, along with CARB and the U.S. Army, even considers JP-8 as an alternative fuel for on-road buses and trucks [3]. However, the 1994 EPA regulations that mandated a maximum allowable sulfur level of 0.05 percent (500 ppm) by weight in diesel fuels for on-highway use effectively denied the Army use of JP-8 on US highways [3].

The objective of this research is to investigate the effect of using JP-8 fuel in a heavy-duty diesel engine on fuel injection, combustion, performance and emissions. The approach relies on detailed in-cylinder and emission diagnostics to tie combustion trends with engine-out parameters. In addition, the insight gained in the study is used to propose dual–use calibration, i.e. modifications of fuel injection strategies required to compensate for possible performance loss associated with using JP-8. Final evaluation of NOx and particulate emission trends is carried out at equivalent performance levels. The engine is equipped with exhaust gas recirculation (EGR), and variable geometry turbocharging (VGT); hence it is expected that results and insight will be useful for studies of low-emission strategies for contemporary production engines regardless of whether they are intended for the Army or commercial fleet owners.

The paper is organized as follows: The background information on relevant fuel properties is given first. This is followed by the description of the test setup and experimental methodology. The discussion of results regarding the performance trends and their relationship with fuel properties and combustion features is next. Detailed analysis of heat release rates provides recommendations for tailoring the fuel injection strategies for JP-8. Subsequently, the emissions trends are evaluated under representative conditions, i.e. for equivalent torque levels. The last section offers conclusions of the study.

FUEL PROPERTIES

The composition of fuel has a strong effect on the quality and quantity of emissions. Variation in fuel properties such as density, cetane number, distillation characteristics, sulfur and aromatic content have all been shown to affect combustion and emissions. Some of these properties are dependent on each other and it is difficult to completely isolate the effect of each. Nevertheless, this section will summarize the relevant properties and consider their changes when diesel fuel is replaced with JP-8. This will be useful in interpreting the results presented in the latter part of the paper and in the context of blending fuels to obtain desirable properties of diesel fuel [7, 8, 9].

DENSITY

A commercially available diesel fuel is made up of a mixture of many different hydrocarbon compounds of various densities and molecular weights. Thus, the overall density is a function of the composition of the fuel. For this reason, there is also an indirect relationship between density and other fuel parameters such as cetane number, viscosity, volatility and distillation characteristics (boiling point range). For example, reducing the high end distillation temperatures will reduce the fuel density by excluding the heaviest compounds.

In diesel engines, fuel is usually injected into the combustion chamber using a volume-based metering system. The JP-8 has a markedly lower density than diesel D-2, as shown in Table 1 summarizing main properties of the two fuels. Lower density will result in lower engine power and will affect specific fuel consumption.

Table 1: Comparison of fuel properties – D-2 vs. JP-8

Properties	***Unit***	***Diesel D-2***	***JP-8***
Cetane Number	-	51	45
LHV (net)	*MJ/kg*	42.9	43.4
	BTU/gal	~129500	~125200
Density (15 °C)	*kg/m^3*	840	805
Viscosity (40 °C)	*cSt*	2.6	1.4
Boiling Point	*°F*	344-635	336-541
Sulfur content	*ppm*	~300	40
Aromatic content	*%*	28.4	13.6

It has also been shown that the density of the fuel can have a direct effect on the build up of fuel pressure in the injection system and a consequent effect on the dynamic start of fuel injection [10]. Compensating for the effect of density on specific power involves adjustment of injection pulse width (duration), but the lower heating value would need to be considered as well.

CETANE NUMBER

The cetane number (CN) of a fuel is a measure of its propensity for autoignition. In other words, it provides a measure of the ignition delay or the time required from the start of fuel injection to the start of combustion. Fuel composition has a strong bearing on its CN. The lower the proportion of straight chained hydrocarbons such as n-hexadecane as compared to branched hydrocarbons, the lower is the CN. The lower the CN, the longer is the ignition delay period. This affects cold-starting, combustion noise and exhaust emissions, e.g. it can reduce PM and increase NOx emissions at high loads [11]. However, a fuel with poor ignition qualities can shift the timing of combustion considerably, especially at high speed-light load operating conditions, and this might lead to incomplete combustion and elevated emissions [12].

HEATING VALUE

For the same mass of fuel injected, a fuel with a higher heating value (mass based) will result in higher heat input to the engine and typically higher cylinder pressures and increased power output. However, from a practical point of view, it is necessary to consider density too, i.e. to compare heating values on a volume basis as well (see Table 1 for D-2 and JP-8). This is due to the fact that fuel economy is customarily expressed in units of volume per mile. Even though diesel fuel has a lower LHV than JP-8 on a mass basis, its higher density leads to a higher heating value on a volume basis.

VISCOSITY

The viscosity is a measure of a fuel's flow properties, such as its resistance to flow. It affects the performance of the fuel injection pump and the injection system. Viscosity is dependent on fuel composition and it can, to some extent, also be correlated with distillation parameters and density. Lower viscosity will result in an increase in leakage losses from the pumping elements, and that in turn might cause a reduction in fuel injected quantity. Pump wear may also increase with lower viscosity as lubricity tends to decrease with viscosity. Viscosity also has an effect on the spray pattern generated by the fuel injectors and as such can strongly affect the performance of the fuel injection system [13].

VOLATILITY

The distillation curve or boiling point range characterizes the volatility of the fuel. The lower the boiling point range the higher the fuel volatility. The distillation characteristics are generated by noting the temperature at which a certain fraction of the fuel is boiled off, typically done in steps of 5%. For example, T85 is the temperature at which 85% of the fuel sample has boiled off. For diesel fuel, the most important distillation characteristics are the temperatures at the top end of the boiling range such as T85, T90, T95 and T99, since these provide a measure of the proportion of heavier components and correlate closely with levels of aromatics. With heavier components in the fuel there is a potential for incomplete vaporization and combustion, especially during cold starting, resulting in increased soot or smoke formation [14].

AROMATIC CONTENT

Aromatics containing multiple benzene rings are known as polyaromatic hydrocarbons or PAH's. They are predominantly present in the heavier fractions of diesel fuel, so their content can be controlled by selectively removing these compounds during the distillation process. As mentioned in an earlier section, the aromatic content has an affect on the density and cetane number of the fuel. It is already known that presence of aromatics in the fuel leads to higher flame temperatures and higher NOx emissions [6, 11, 15]. Additionally, since the concentration of aromatics affects the C/H ratio of the fuel, it is reasonable to expect that this would have an impact on soot formation. In fact, PAHs are considered precursors for soot formation and affect significantly the nucleation of particles in the submicron range [16, 17]. Reduced PAH has been shown to have a significant benefit on PM for older engines, and it is being suggested that the PAH content and not the total aromatic content of the fuel is what needs to be controlled for PM reduction. However a study conducted by Hountalas, et al. [10] did not find a substantial effect of PAH content on smoke emissions.

SULFUR CONTENT

Currently, fuels designated for use in the diesel engine have a sulfur limit of 500 ppm by weight (Low Sulfur Diesel or LSD). New standards will lower this significantly, since the 2006 EPA regulations require all diesel fuel to contain no more than 15 ppm of sulfur. This will drastically reduce the amount of sulfates from the exhaust and will be an enabler for the aggressive use of exhaust gas recirculation and aftertreatment technologies. As seen in Appendix A, the JP-8 fuel used in the study had a fuel sulfur content of only 40 ppm, which indicates the trend of voluntarily reducing sulfur content even for jet fuel. The fuel analysis of both fuels was conducted at Paragon Laboratory in Livonia, Michigan.

SUMMARY OF FUEL PROPERTIES

The study was conducted using 2 fuels -- premium Amoco Diesel Fuel, found to contain 300 ppm sulfur and 28.4% aromatic content, and military-grade JP-8 aviation fuel, with ultra low sulfur (40 ppm) and 13.6% aromatic content. Most relevant properties of both fuels are given in Table 1.

The lower density of JP-8 will have to be taken into account when examining performance trends. JP-8 has a lower cetane number as compared to regular diesel fuel; hence it is expected to have a higher ignition delay [4]. The lower viscosity of JP-8 will be a factor in evaluating injection system behavior. The lower heating value of JP-8 on a per volume basis is somewhat smaller, but if the fuel injection volume is increased to provide matching of the mass of fuel injected, the JP-8 should have an advantage over D-2. Finally, a combination of higher volatility and lower sulfur content of JP-8 will contribute to emissions trends.

EXPERIMENTAL SETUP

The engine used in the study is a Detroit Diesel Corporation (DDC) Series 60 heavy-duty diesel engine. The engine is equipped with electronic unit injection (EUI), variable geometry turbocharging (VGT), and exhaust gas recirculation (EGR) with EGR cooler and charge air intercooler. The VGT swing blade settings are controlled through a PWM signal sent to a compressed air actuator (VPOD). The engine control software, DDEC IV, allows control over the VGT setting, the EGR flow, start of injection (BOI) and duration of injection (pulse width – PW). Complete engine specifications are given in Table 2, while Figure 1 shows the view of the engine exhaust side, with the VGT, EGR valve and EGR cooler in the forefront.

Table 2: Engine Specifications

Total Displacement	12.7 liters, 6 cylinder
Breathing	Turbocharged, intercooled
Fuel Injection	Electronic Unit Injector
Fuel Pressure	Camshaft actuated pump
Bore x Stroke	130 x 160 mm
Compression Ratio	15:1
Rated Torque / Speed	2035 N-m / 1200 RPM
Max Power / Speed	350 kW / 2100 RPM
Intake Valve Open	36 CA deg BTDC
Intake Valve Close	40 CA deg ABDC
Exhaust Valve Open	37 CA deg BBDC
Exhaust Valve Close	75 CA deg ATDC
Valve Overlap	111 CA deg

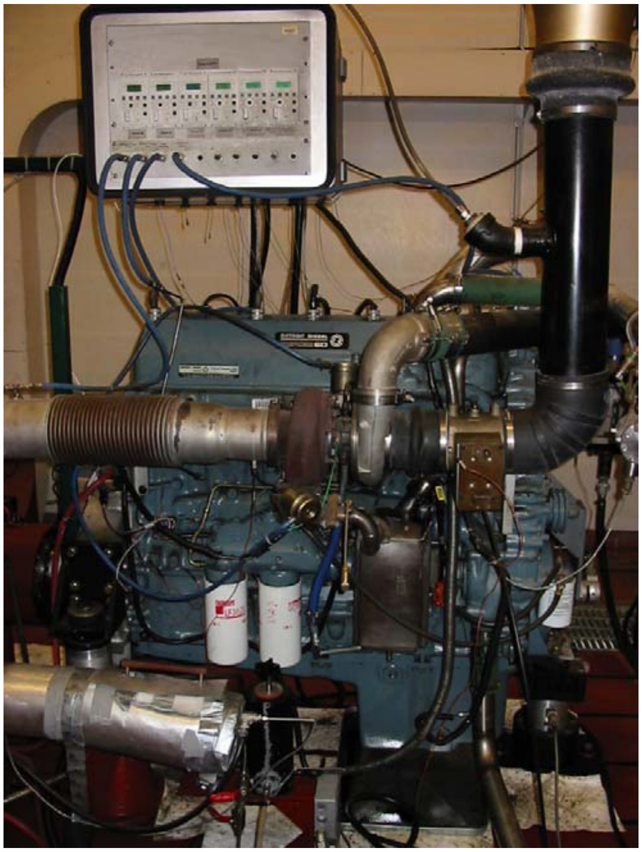

Figure 1: Experimental Setup

The engine and test cell are fully instrumented to measure engine operating parameters and enable diagnostics of in-cylinder processes. Engine speed and torque, as well as temperatures, pressures and flows at different locations in the engine system are recorded as a function of time using the low speed data acquisition system. The high speed system records engine cycle variables every quarter crank angle degree, namely in-cylinder pressure, fuel injection pressure via a rocker arm strain gauge, and instantaneous combustion chamber surface temperatures. More details on fuel injection pressure measurements and its use for determining the dynamic start of injection are given by Filipi et al. in [18], and additional data regarding cylinder-pressure-based diagnostics and heat release analysis is provided by Jacobs et al. in [19]. The emissions bench is capable of measuring CO, CO_2, O_2, NO_x and HC emissions on a dry basis, and the results are subsequently converted to a wet basis. A mini-dilution tunnel developed in-house was used for gravimetric or mass-based measurement of Particulate Matter [20]. In addition, the AVL 415S Variable Sampling Smoke Meter was used to measure the smoke levels in the exhaust.

METHODOLOGY

The main objective is to understand the effect of JP-8 fuel on combustion, performance and emissions of a heavy-duty diesel engine. Performance and fuel economy indicators are assessed first. The engine is operated at the following speed – load combinations: 1200 rpm, 20% load (low rpm - low load), 1200 rpm, 50% load (low rpm - mid load), and 1500 rpm, 75% load (mid rpm - high load). These operating points were selected as representative of some typical in-vehicle conditions, such as Low-Speed Steady Cruise, Mid-Speed Steady Cruise, and High-Speed Cruise or Hill Climb, based on a previous study with diesel fuel completed at the University of Michigan [20].

The combustion and injection diagnostics are then correlated with performance trends in order to explain them and devise strategies for matching engine output with JP-8 to that of a production diesel-fueled engine. As an example, the fuel density effect can obviously be compensated through variations of the injection pulse width. However, effects of fuel compressibility and viscosity are much more subtle. Thus, only a rigorous evaluation of injection pressure trends combined with assessments of the impact of lower cetane number on ignition delay can provide quantitative guidance regarding injection timing strategy. Making suitable adjustments to ensure the unchanged start of combustion with JP-8 enables full understanding of the effect of fuel composition on the rate of heat release and emissions.

The assessment of emissions trends with JP-8 were addressed after the analysis of performance, injection and combustion yielded conditions allowing representative comparisons. The aim is to obtain in-depth insight into the effects of JP-8 on emissions and to evaluate the overall emissions potential in quantitative terms for a comparable engine output level. In-cylinder emission control measures currently employed on heavy-duty diesel engines, namely exhaust gas recirculation (EGR) and variable geometry turbocharging (VGT), along with injection timing and pulsewidth are also considered as potential additional factors that can be compounded with fuel effects. The ultimate goal is to utilize detailed insight for identifying strategies for matching or possibly improving performance and emissions with JP-8, as compared to the base diesel calibration.

It should be noted here that all comparisons at an individual speed - load condition were done with constant baseline VGT setting and without EGR, with the exception of NOx-PM tradeoffs, where EGR and injection timing were varied. This eliminates the effect of VGT and EGR on the performance trends, which are discussed next.

RESULTS – PERFORMANCE TRENDS

To evaluate the total performance effects of applying JP-8 instead of diesel fuel, the engine was operated at 1200 rpm and 20% load with base injection timing, pulse width (PW) and VGT setting. Engine torque, Brake Specific Fuel Consumption (BSFC), boost pressure and mass flow rate of fuel are shown in Figure 2. Focusing first on two sets of results corresponding to same fueling PW, a substantial drop in both fueling rate on a mass basis (-11.7%) and brake torque (-13.7%) with JP-8 is evident.

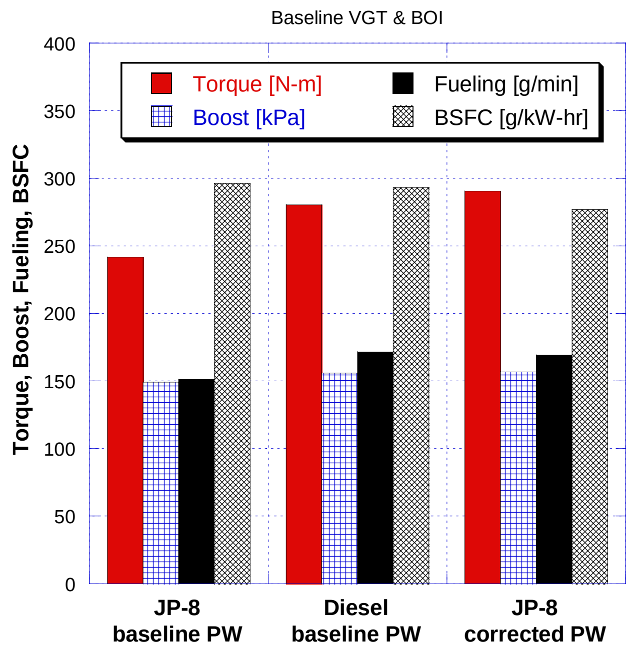

Figure 2: Performance at 20% load, with and without adjustment of pulse width for JP-8 operation

The drop in fueling is attributed to two factors, namely lower density of JP-8 fuel (-4.2%) and increased leakage losses in the unit injector system due to lower viscosity. The drop in torque can directly be attributed to the lower fueling rate, more than offsetting a slightly higher net heating value of JP-8 on a mass basis. The boost pressure is reduced by -4.4% due to a drop in exhaust enthalpy available for driving the turbocharger. There is a minor increase in fuel consumption or BSFC (+1%), most likely due to a relative increase of mechanical losses at the lower output level. Similar observations can be made regarding the performance at the 50% load point and 1200 rpm shown in Figure 3.

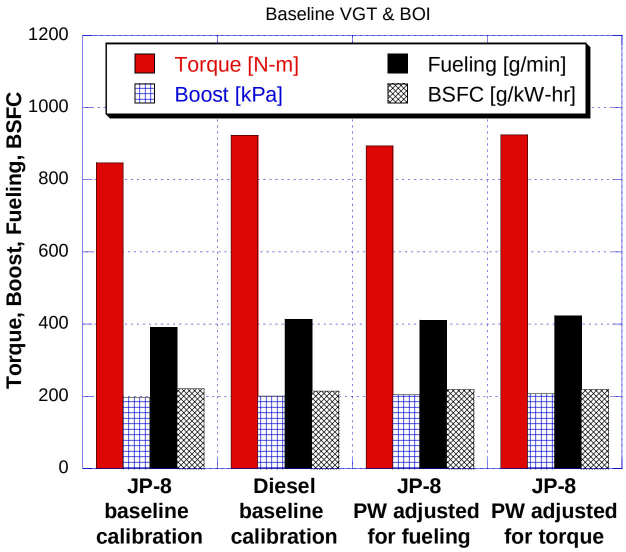

Figure 3: Performance at 50% load, with and without adjustment of injection pulse width for JP-8 operation

COMPENSATING FOR LOWER FUELING BY INCREASING INJECTION DURATION

The reduction of fueling rate due to lower density of JP-8 can obviously be eliminated by increasing the pulse width of injection. The increased injection volume producing a constant fuel mass flow rate is then used for all subsequent comparisons with baseline diesel fuel operation.

As shown in Figure 2, at 1200 rpm 20% load, it is possible to compensate for the lower density of JP-8 fuel and the higher leakage losses by increasing the injection pulse width to match the mass-fueling rate obtained with diesel fuel. The result is a slightly higher torque than baseline (+3.6%), accompanied by increased boost and lower BSFC. Evaluation of the specific fuel consumption on a volume basis after PW adjustment showed that it is ~1% lower than with D-2, a surprising finding that can be attributed to the slightly higher energy content of the JP-8 on a mass basis. This is particularly important from the customer point of view, since the fuel is typically bought and sold on a volume basis.

Figure 4 breaks down further the effect of JP-8 on performance variations at the 20% load level, via the relevant mean effective pressure variables. The gross IMEP with JP-8 fuel is higher than that obtained with diesel fuel and an equal mass injected, due to the higher net heating value of JP-8 in (J/kg). There is also a slight increase in friction losses. This is attributed to the higher effective stroke associated with longer PW and the leakage losses occurring in the unit injector. The hypothesis about increased leakage losses stems from the significantly lower viscosity of JP-8.

At medium load, i.e. 1200 rpm 50% torque point shown in Figure 3, matching of the baseline performance when running with JP-8 was a two-step process. Matching the mass of fuel injected did not produce exactly the same torque, due to the losses in the fuel injection system. A slight further increase of pulse width and hence a slightly higher fueling rate than with D-2 baseline enabled matching the torque with a marginal difference in specific fuel consumption values.

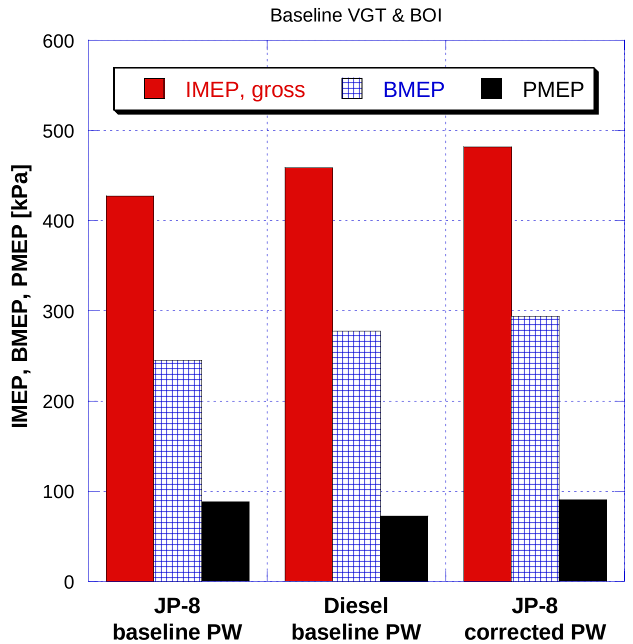

Figure 4: Comparison of mean effective pressures, JP-8 vs. D-2 fuel, 20 % load. Fueling matched on pulse width or injected mass basis

In summary, the performance of the baseline diesel operation can be matched by increasing the volume of injected JP-8. While it is sufficient to match the mass of fuel injected at lower loads, the apparent increase of mechanical losses in the fuel injection system requires further increases of fueling with JP-8 at higher loads. This has to be taken into account when specifying the fuel injection hardware for a multi-fuel engine, as the high-pressure pump has to be capable of delivering required maximum amounts of JP-8 fuel. When the performance is matched, the BSFC values are also very close to baseline.

Dynamic Injection Timing

Measurement of injection pressure profiles shown in Figure 5 reveals that JP-8 causes a change of the injection pressure gradient. It can be tied to higher bulk compressibility and lower viscosity of the JP-8 fuel. Consequently, peak pressure even for increased PW is lower than that achieved with D-2 fuel, and there is a delay of dynamic injection on the order of 0.25 CA. Further analysis of injection and ignition timing will show whether this variation will have to be accounted for in recalibration of the engine for JP-8 fuel.

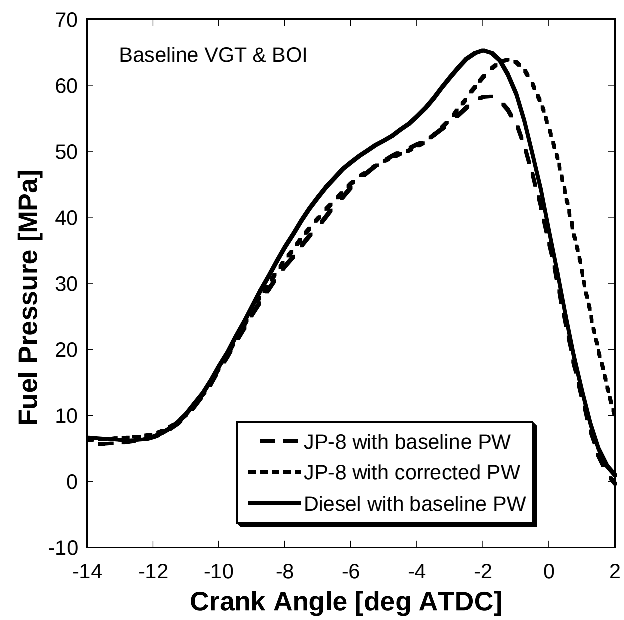

Figure 5: Injection pressure profiles obtained with diesel fuel and JP-8; baseline and adjusted injection pulse widths.

Heat Release

Figure 6 shows heat release curves for the baseline case and JP-8 cases operated with different pulse widths. Results correspond to the 1200 rpm – low load case. The heat release profiles indicate increased premixed burn fraction associated with combustion with JP-8 fuel as compared to diesel. Even in the case of highest pulse width, the peak of the premixed spike with JP-8 is higher than that of the diesel-fueled engine. This can clearly be attributed to a higher ignition delay and increased accumulation of fuel in the combustion chamber prior to ignition.

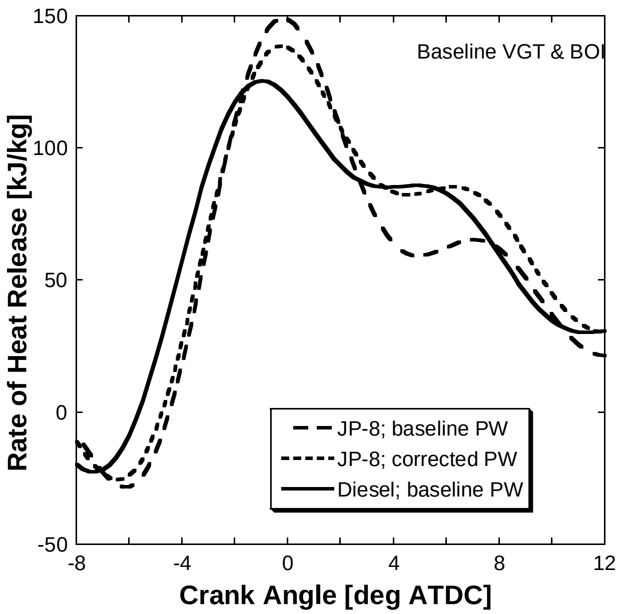

Figure 6: Effect of JP-8 on heat release profiles at 1200 rpm and 20% load

The ignition delay is calculated based on the difference between Start of Combustion (SOC) and the Dynamic Start of Injection (SOI). The SOC is determined from the rate of heat release (RHR) profile as the beginning of the positive slope of the RHR line. The SOI is determined from the injection pressure profile and the experimentally confirmed needle lift opening pressure [6]. Figure 7 summarizes the injection and ignition delay trends. The ignition delay for the JP-8 case with the PW equal to that of the diesel baseline is greater by roughly a degree CA. However, when PW is increased, ignition delay slightly decreases due to higher in-cylinder temperatures at the time of fuel injection, but not quite enough to match the value obtained with D-2.

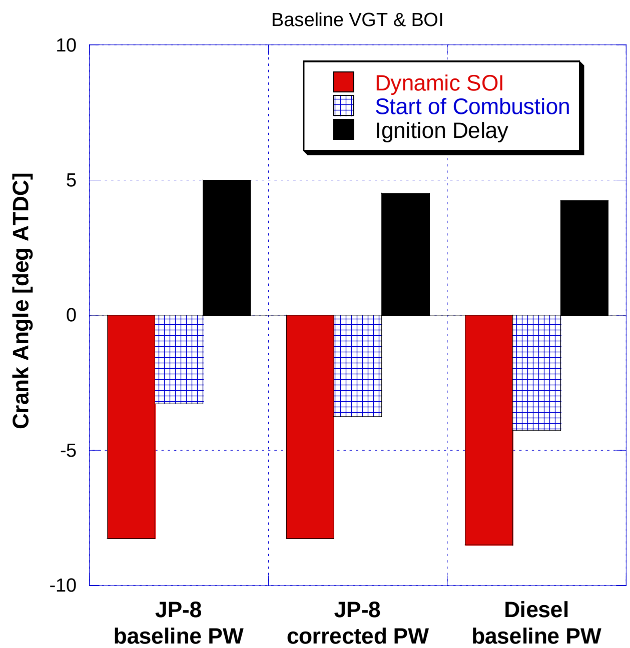

Figure 7: Dynamic start of injection, start of combustion and ignition delay at 1200 rpm 20% load

A number of fuel properties can have impact on ignition delay, but the primary effect is expected from the cetane number and fuel volatility. As shown in Table 1, JP-8 has a lower CN than diesel (46 vs. 51) and that directly increases ignition delay. In contrast, the higher volatility could lead to better mixture preparation and a shorter ignition delay. The overall clear trend of increased ignition delay with JP-8 indicates a much more dominant role of the cetane number.

Burn rates obtained at higher load (50%) and 1200 rpm are given in Figure 8. The basic trends of increased ignition delay with JP-8 fuel do not change. A higher premixed burn spike is followed by the somewhat retarded diffusion burn profile in the case of JP-8 combustion. At the first glance, the heat release profile for JP-8 fuel appears to be retarded even for the equal pulse width due to the delayed start of combustion. However, combustion ends roughly at the same time in all cases, indicating that the increased portion of JP-8 fuel rapidly burning in the premixed phase compensates for its delayed ignition.

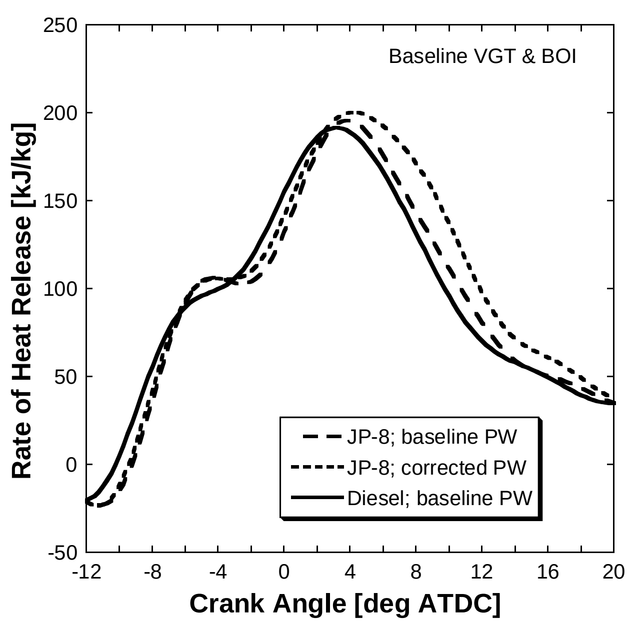

Figure 8: Effect of JP-8 on heat release profiles at 1200 rpm and 50%

In short, operation with JP-8 produces an ignition delay difference of about 1.5 deg CA at 1200 rpm 50% load. When this is added to the 0.25 deg CA delay in dynamic SOI, there is about 1.75 deg difference in the time from generation of solenoid pulse to start of combustion when compared to diesel fuel. However, burning is somewhat faster due to increased fraction of premixed burning. An advance of injection timing could compensate for the prolonged ignition delay, but the effect of that on performance will depend on the overall combustion phasing being the function of both ignition timing and combustion duration.

COMPENSATION FOR INCREASED IGNITION DELAY

An attempt is made to compensate for the increases in ignition delay with the JP-8 fuel by using advanced injection timing. For 1200 rpm and 50% load, the timing was advanced by 2 degrees, i.e. from nominally 16 deg BTDC to 18 deg BTDC. This allows combustion to start slightly earlier in the cycle with JP-8 fuel (-0.5 deg), but the previously observed increases in the premixed burn fraction and the peak value of the RHR remain (see Figure 9).

Considerations of brake torque and fuel consumption show no benefit of advanced injection timing. It appears that advancing the timing moves combustion phasing away from the optimum obtained at 16 deg

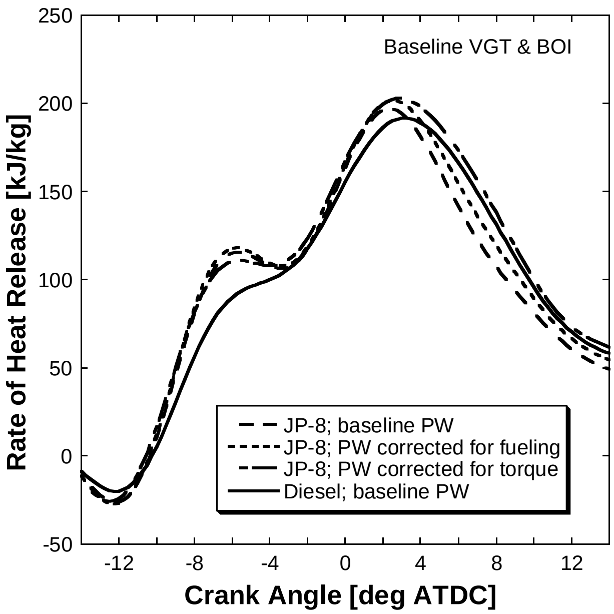

Figure 9: Effect of Injection Timing on Heat Release

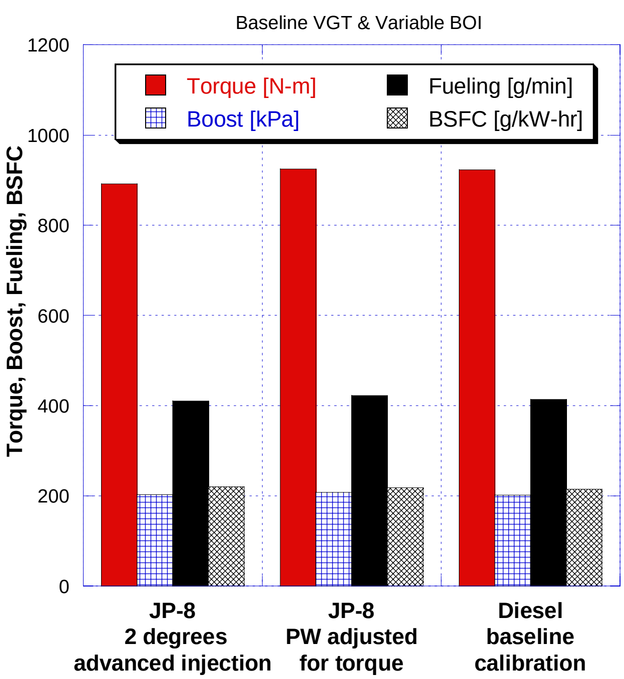

Figure 10: The effect of advancing the injection timing by two degrees – 50% load, 1200 rpm; mass of fuel injected adjusted for required torque level.

BOI. This can be linked primarily to the high premixed burn fraction with JP-8. Detailed comparisons of performance and fuel economy parameters are given in Figure 10. Trends were similar at other operating conditions. Thus, calibration tailored for operation with JP-8 does not have to include the correction for injection timing.

RESULTS – EMISSIONS TRENDS

Figure 11 compares the NOx and PM emissions from the engine operated with the JP-8 and diesel fuel at 1200 rpm 20% load. There is a dramatic reduction of NOx emissions with JP-8 fuel regardless of the fuel mass compensation, e.g. a 32% reduction is observed for the baseline pulse width and 35% for the increased pulse width. A similar reduction of NOx values with JP-8 fuel is seen at 50% load as shown in Figure 12. This large drop in NOx values with JP-8 is in conflict with the observed higher ignition delay and premixed burning. Obviously, there is another factor influencing combustion and causing lower temperatures in the reaction zone. No direct measurements of flame temperature were possible; however examining instantaneous surface temperatures provides an indirect way of evaluating trends. Measurements were carried out with fast-response J-type thermocouple probes installed flush with the combustion chamber wall. The probes are originally designed for heat flux measurements and engine heat transfer studies. More details about instrumentation are given by Chan et al. [21]. As shown in Figure 13, the surface temperature for operation with diesel fuel is higher than in the case of JP-8 and this is a good indication of lower peak

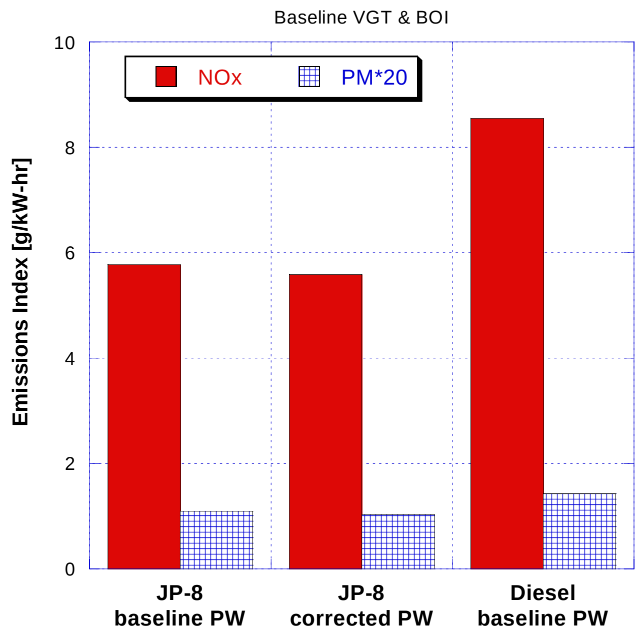

Figure 11: Comparison of NOx and PM emissions with JP-8 and baseline D-2 fuel, 1200 rpm 20% load

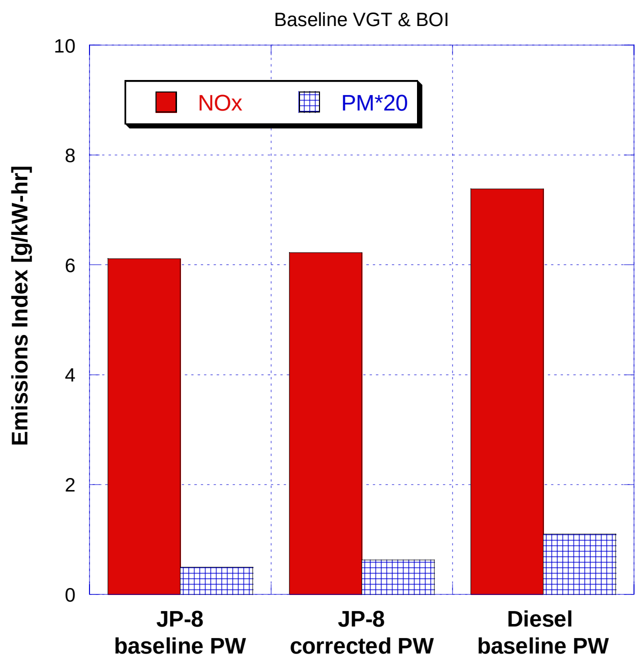

Figure 12: Comparison of NOx and PM emissions with JP-8 and baseline D-2 fuel, 1200 rpm 50% load.

flames temperatures occurring with JP-8 fuel. This is likely due to the lower aromatic content of the fuel.

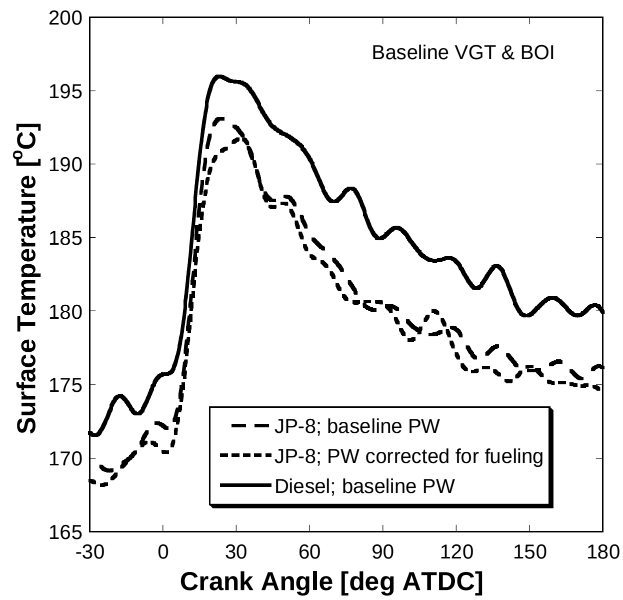

Figure 13: Instantaneous surface temperature measured with diesel fuel and JP-8

When it comes to soot emissions, it was expected that the higher fuel volatility and prolonged ignition delay would lead to better fuel-air mixing. Better mixing implies fewer rich pockets in the combustion chamber and reduction of soot formation. Indeed, results in Figures 11 and 12 indicate overall reduction of emitted particulate matter. An additional effect could be the lower sulfur content of the JP-8 fuel, leading to lower content of sulfates in particulate matter.

Encouraging findings regarding both NOx and PM emissions with JP-8 fuel motivate further studies utilizing the NOx – PM tradeoff plots. The intention is to provide guidance for maximizing the emission benefit with JP-8 through tailoring of the injection and EGR parameters. Figure 14 shows a typical NOx-PM tradeoff curve for the EGR sweep performed at constant injection timing (BOI). The NOx - PM curve for JP-8 fuel is shifted significantly southwest as compared to diesel, due to simultaneous reduction of NOx and PM emissions. As explained earlier, the lower PM emissions are attributed mainly to higher fuel volatility and lower sulfur, while the lower NOx primarily to the lower aromatic content. A deviation seen on the line for D-2 close to 5% EGR can be explained by system effects. The adjustment of the VGT setting going from 5% to 10% EGR causes a simultaneous increase of boost, therefore providing a more air for combustion and moving the point slightly in the direction of lower PM.

Similar trends are observed at the higher load (50%), as seen in Figure 15. The NOx reduction is not as prominent at the higher load setting. However, this is accompanied by an impressive reduction of PM, particularly at moderate EGR levels. It is interesting to note that the tradeoff based on specific emission did not change when switching from the baseline calibration (constant PW) to increased pulse width for JP-8 (constant mass). The comparison for constant PW looked exactly the same as corresponding plots in Figs. 14 and 15; therefore it is sufficient to analyze comparisons based on constant fueling mass.

The sensitivity of emission to injection timing can be assessed from Figure 16, displaying three NOx-PM tradeoff lines obtained with JP-8 and different injection timings. The overall shape of the profiles is

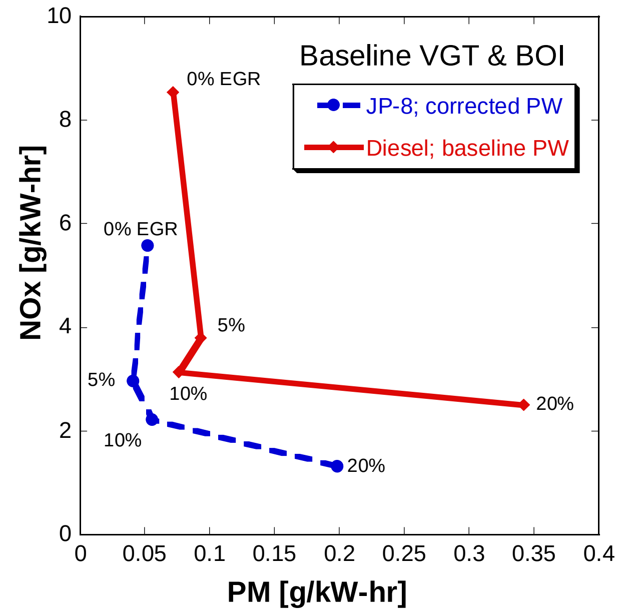

Figure 14: Comparison of the NOx-PM emissions tradeoff at 20% Load

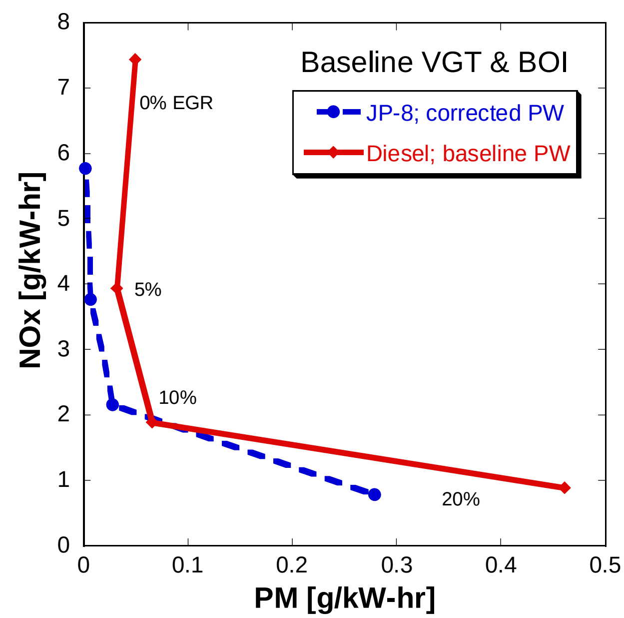

Figure 15: Comparison of the NOx-PM emissions tradeoff at 50% Load.

similar, and the lines are relatively close together. In other words, very similar emission levels can be achieved with different combination of BOI and EGR, and the ultimate decision depends on fuel economy and other considerations, e.g. thermal loads. Not unexpectedly, the optimum point at the inflection of the curve is shifted in the direction of lower NOx with timing retarded to BOI=12 degress BTDC. The significant shift of the tradeoff towards lower PM levels with JP-8 is confirmed regardless of the injection timing.

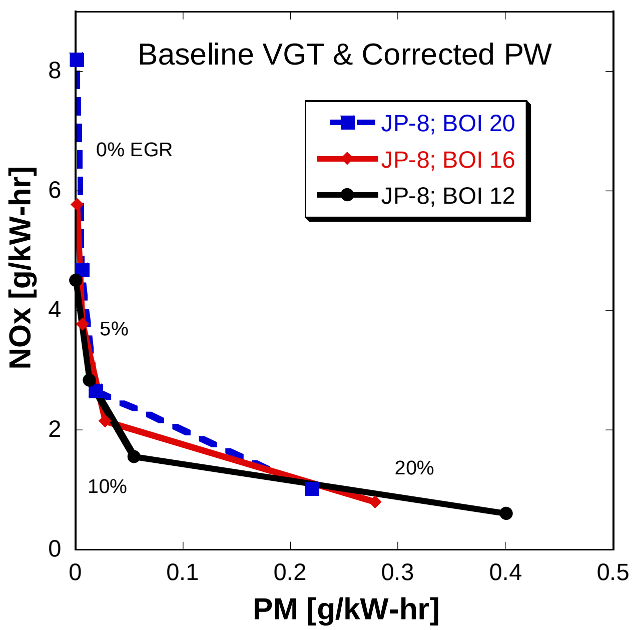

Figure 16: NOx-PM Tradeoff for JP-8 and EGR sweeps with different injection timings; 1200 rpm 50% Load

CONCLUSION

An investigation is carried out to evaluate the effect of using JP-8 fuel in a heavy-duty diesel engine on fuel injection, combustion, performance, and emissions. The study subsequently utilizes the obtained insight to propose engine calibration capable of minimizing penalties and maximizing potential benefits. Experiments were conducted on a Detroit Diesel Corporation (DDC) S60 engine outfitted with EGR. The approach was focused on understanding the mechanisms behind differences caused by replacing the diesel fuel with JP-8, and subsequently defining conditions for rigorous comparisons at the same performance levels and representative combustion conditions. The findings of this study can be summarized as follows:

- Directly replacing diesel fuel with JP-8 leads to performance reduction due to lower density and consequently smaller mass of fuel injected for the same injection pulse width.

- It is possible to match the performance of the engine with diesel fuel by increasing the pulse width of JP-8 injection to match the mass of fuel per stroke.

- The correction of injection pulse width at higher loads may need to go beyond direct compensation for lower density of JP-8, due to increased mechanical losses in the fuel system pumping higher rates of volumetric flow.

- The higher compressibility of JP-8 fuel causes slower pressure build up in the high-pressure fuel pump element as compared to diesel fuel. In addition, the lower cetane number of JP-8 leads to higher ignition delay, retarded start of combustion and increased fraction of premixed burning. However, advancing the injection timing is not recommended, since the overall effect leads to non-optimum combustion phasing and slight deterioration of performance.

- Under all conditions, testing with JP-8 fuels yielded lower NOx and PM emissions. In particular, the soot formation is drastically reduced due to beneficial effects of higher volatility of fuel and the higher ignition delay on mixing. Simultaneous reduction of NOx is attributed to lower aromatic content of JP-8. The beneficial effect of EGR on emission tradeoffs is relatively unchanged with JP-8. The overall trends captured with the NOx-PM tradeoff curves are shifted in the direction of lower optimum, with a strong bias towards lower PM.

ACKNOWLEDGEMENT

The authors wish to acknowledge the technical and financial support of the Automotive Research Center (ARC) by the National Automotive Center (NAC), and the U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC). The ARC is a U.S. Army Center of Excellence for Automotive Research at the University of Michigan, currently in partnership with the University of Alaska-Fairbanks, Clemson University, University of Iowa, Oakland University, University of Tennessee, and Wayne State University.

REFERENCES

1. Moran, T. “The Logistics Battle: U.S. wages a one-fuel war”, Automotive News Article 43091, 2003
2. U.S. Army Tank Automotive and Armaments Command, “JP-8: The Single Fuel Forward – An Information Compendium”, 2001
3. Yost, D., Montalvo, D.A., and Frame, E.A. “U.S. Army Investigation of Diesel Exhaust Emissions Using JP-8 Fuels with Varying Sulfur Content, SAE 961981, 1996
4. Kotsiopoulos, P.N., Yfantis, E.A., and Hountalas, D.T. “Comparative Results of the Use of Diesel Fuel and JP-8 Aviation Fuel on a DI Diesel Engine”, SAE 974007, 1997
5. Frame, E.A., Alvarez, R.A., Blanks, M.G., Freerks, R.L., Stavinoha, L.L., Muzzell, P.A., Villahermosa, L., “Alternative Fuels: Assessment of Fischer-Tropsch Fuel for Military Use in a 6.5L Diesel Engine, SAE 2004-01-2961
6. Korres, D., Lois, E., and Karonis, D. “Use of JP-8 Aviation Fuel and Biodiesel on a Diesel Engine”, SAE 2004-01-3033, 2004
7. Sirman, M.B., Owens, E.C. and Whitney, K.A. “Emissions Comparison of Alternative Fuels in an Advanced Diesel Engine”, SAE 2000-01-2048, 2000
8. Uchida, M. and Akasaka, Y. “A Comparison of Emissions from Clean Diesel Fuels”, SAE 1999-01-1121, 1999

9. Thornton, M. “Impact of Future Fuels on Emission Control Systems”, 2nd Annual Summer Conference on Automotive Simulation Technology, 2004
10. Hountalas, D. and Kouremenos, D. “Experimental Investigation of the Effect of Fuel Composition on the Formation of Pollutants in Direct Injection Diesel Engines”, SAE 1999-01-0189, 1999
11. Kidoguchi, Y., Miwa, K., and Yang, C. “Effects of Fuel Properties on Combustion and Emission Characteristics of a Direct Injection Diesel Engine”, SAE 2000-01-1851, 2000
12. Nylund, N.O. and Aakko, P. “Characterization of New Fuel Quantities”, SAE 2000-01-2009, 2000
13. Callahan, T.J., Ryan, T.W., Dodge, L.G., and Schwalb, J.A. “Effects of Fuel Properties on Diesel Spray Characteristics”, SAE 870533, 1987
14. Wall, J.C. and Hoekman, S.K. “Fuel Composition Effects on Heavy Duty Diesel Particulate Emissions”, SAE 841364, 1984
15. Ullman, T.L., Spreen, K.B., and Mason, R.L. “Effects of Cetane Number, Cetane Improver, Aromatics and Oxygenates on 1994 Heavy Duty Diesel Engine Emissions”, SAE 941020, 1994
16. Lapuerta, M., Hernandez, J.J., Ballesteros, R., and Duran, A. “Composition and Size of Diesel Particulate Emissions from a Commercial European Engine tested with Present and Future Fuels”, IMechE Vol 217 Part D - D08902, 2003
17. Lombaert, K., le Moyne, L., Tardieu de Maleissye, J., and Amouroux, J. “Analysis of Diesel Particulates: Influence of Air Fuel Ratio and Fuel Composition on Polycyclic Aromatic Hydrocarbon Content”, Int J Engine Research Vol 3 No 2 Pg 103-113, 2002
18. Filipi, Z. S., Homsy, S. C., Morrison, K. M., Hoffman, S. J., Dowling, D. R., Assanis, D. N. ”Strain Gage Based Instrumentation for In-Situ Diesel Fuel Injection System Diagnostics”, Proceedings of the 1997 ASEE Annual Conference, paper 225903, Milwaukee, June 15-17, 1997
19. Jacobs, T., Filipi. Z., Assanis, D. ”The Impact of Exhaust Gas Recirculation on Performance and Emissions of a Heavy-Duty Diesel Engine”, SAE paper 2003-01-1068, Warrendale, PA, 2003
20. Williamson, W. “Effect of Exhaust Gas Recirculation (EGR) in Examining the NOx Versus Particulate Matter Emissions Tradeoff in a Heavy Duty Diesel Engine”, Master’s Thesis, Deptartment of Mechanical Engineering, University of Michigan, 2004
21. Chang, J., Filipi, Z., Assanis, D., Kuo, T.-W., Najt, P., Rask, R. “New Heat Transfer Correlation for the HCCI Engine Derived from Measurements of Instantaneous Surface Heat Flux”, SAE paper 2004-01-2996, SAE Transactions, Journal of Engines; 2004

APPENDIX – FUEL ANALYSIS OF JP-8 FUEL

Parameter	Result	RDL	Dil.	Units	Qual.	Method
Distillation Degrees F						
Initial Boiling Point	336.2	0.1	1	deg. F		ASTM D86
5.0% Recovery	362.8	0.1	1	deg. F		ASTM D86
10.0% Recovery	365.7	0.1	1	deg. F		ASTM D86
20.0% Recovery	373.6	0.1	1	deg. F		ASTM D86
30.0% Recovery	379.2	0.1	1	deg. F		ASTM D86
40.0% Recovery	385.5	0.1	1	deg. F		ASTM D86
50.0% Recovery	392.9	0.1	1	deg. F		ASTM D86
60.0% Recovery	401.5	0.1	1	deg. F		ASTM D86
70.0% Recovery	412.1	0.1	1	deg. F		ASTM D86
80.0% Recovery	426.0	0.1	1	deg. F		ASTM D86
90.0% Recovery	448.3	0.1	1	deg. F		ASTM D86
95.0% Recovery	477.6	0.1	1	deg. F		ASTM D86
End Point	541.0	0.1	1	deg. F		ASTM D86
% Overhead Recovery	98.2	0.1	1			ASTM D86
% Residue	1.6	0.1	1			ASTM D86
% Loss	0.2	0.1	1			ASTM D86
350.0 Deg.F % Recovery	1.8	0.1	1	mL		ASTM D86
400.0 Deg.F % Recovery	58.8	0.1	1	mL		ASTM D86
Elemental Analysis						
Wt% of Carbon	86.13	0.05		mass %		ASTM D5291
Wt% of Hydrogen	13.87	0.05		mass %		ASTM D5291
FIA - Oxgenate Free Basis						
Avg. % Vol of Saturates Zone	85.1	0.1		% v/v		ASTM D1319
Avg. % Volume of Olefins Zone	1.3	0.1		% v/v		ASTM D1319
Avg. %Vol of Aromatics Zone	13.6	0.1		% v/v		ASTM D1319
Petroleum						
Cetane No.	46.2		1			ASTM D613
Density @ 15.56 deg C	0.8056	0.0001	1	g/mL		ASTM D4052
Total Sulfur (Microcoulometry)	40	1	1	ppm wt.		ASTM D3120
Viscosity, Kinematic @40 deg C	1.336	0.2	1	mm2/sec		ASTM D445
Gross Heating Value (BTU/lb)	19905		1	BTU/lb		ASTM D240
Gross Heating Value (mJ/kg)	46.299		1	mJ/kg		ASTM D240
Net Heating Value (BTU/lb)	18640		1	BTU/lb		ASTM D240
Net Heating Value(mJ/kg)	43.356		1	mJ/kg		ASTM D240
Stoichiometric Ratios						
H/C Atomic Ratio	1.919	0.001				SAE J1829
O/C Atomic Ratio	<0.001	0.001				SAE J1829
C/H Ratio	6.2100	0.001				SAE J1829
Air/Fuel Ratio	14.67	0.01				SAE J1829